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REPORT DOCUMENTATION PAGE

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1. REPORT NUMBER AIAA Paper No. 74-333	2. GOVT ACCESSION NO.
3. RECIPIENT'S CATALOG NUMBER	
4. TITLE (and Subtitle) (6) Supercritical Planing Hulls (U)	5. TYPE OF REPORT & PERIOD COVERED
	6. PERFORMING ORG. REPORT NUMBER
7. AUTHOR(s) (10) Peter R. Payne	8. CONTRACT OR GRANT NUMBER(s)
9. PERFORMING ORGANIZATION NAME AND ADDRESS Payne, Incorp. Annapolis, MD	10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS
11. CONTROLLING OFFICE NAME AND ADDRESS	12. REPORT DATE (11) Feb[illegible]74
	13. NUMBER OF PAGES 19
14. MONITORING AGENCY NAME & ADDRESS (If different from Controlling Office) (12) 22	15. SECURITY CLASS. (of this report) UNCLASSIFED
	15a. DECLASSIFICATION/DOWNGRADING SCHEDULE

16. DISTRIBUTION STATEMENT (of this Report)

Unlimited and approved for Public release.

DTIC ELECTE FEB 29 1980 S D A

17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)

18. SUPPLEMENTARY NOTES

This report used by OP-96V in their study: Advanced Naval Vehicles Concepts Evaluation.

19. KEY WORDS (Continue on reverse side if necessary and identify by block number)

Advanced Naval Vehicles Concepts Evaluation
ANVCE
Parametrics and Point Designs
Planing Hulls
SEA KNIFE

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

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AIAA Paper No. 74-333

SUPERCRITICAL PLANING HULLS

by
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AIAA/SNAME Advanced Marine Vehicles Conference

SAN DIEGO, CALIFORNIA / FEBRUARY 25-27, 1974

SUPERCRITICAL PLANING HULLS

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Abstract

The intolerable pounding of conventional planing hulls is the chief reason for the development of alternative hydrofoil and SES vehicles, in an attempt to achieve high speeds with motions that are commercially and militarily acceptable. Our approach has been to find out why a conventional planing hull pounds, and then to devise new planing hull forms which avoid the problem. Work over the last ten years, including a dozen experimental boats, has resulted in forms which largely meet this objective, we believe. Experimental data indicates that our latest hull - the Sea Knife - has a better ride than SES or surface-piercing hydrofoils, and for a much lower cost, is not much inferior to the fully-submerged hydrofoil.

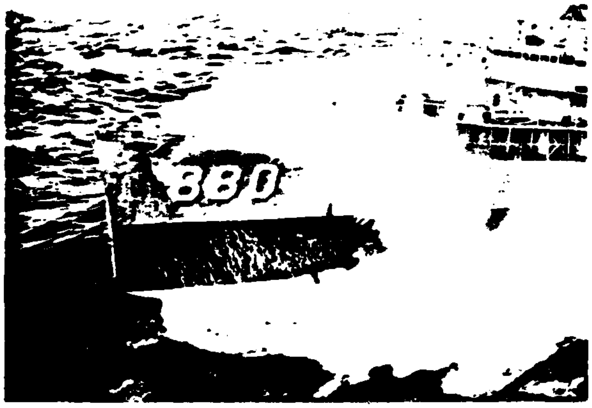

Figure 1. The Sea

Introduction

For the past decade, Payne Inc. has been exploring the world of super-critical hulls. By this, we mean a hull which is so soft in pitch and heave that it responds only sluggishly to the waves as they speed by - very much as an automobile body responds only slightly to a washboard road. I should perhaps mention, right at the outset, that all of this work has been privately funded - much of it from my very limited pocket - so that our program has proceded in fits and starts, and in a not very efficient fashion. If some of our procedures seem a bit primitive, please reflect, before criticizing, how you would have done it in the absence of any government contract.

For the case of the pitching motion of a conventional displacement hull in regular head seas, amplitudes of motion are greatest near synchronism, when the period of encounter with the waves - which depends on ship speed and wave length - equals the ship's natural period of oscillation. Phase relationships leading to deck immersion and slamming are also characteristic of synchronism. In practice, when such resonance occurs, a speed reduction or change of heading is usually employed to ease the ship. At a low enough speed, loosely speaking, the ship will be responding to the waves without dynamic amplification.

Resonance can also be avoided, however, by speeding up the ship. It will then tend to cut through the waves rather than rise to the on-coming crests, and is said to be operating "super-critically." The phenomenon can be observed in a high speed passenger liner or a destroyer being driven in rough - but not too rough - head seas.**

If only hydrostatic forces were of importance, then it would be true to say that the faster a super-critical ship travels, the smoother it would ride, until the speed was high enough for dynamic instability. But in practice, the only "conventional" hulls capable of making such high speeds are planing craft, which avoid the wave-making resistance barrier to high speed by utilizing dynamic forces to lift them on top of the water surface. The dynamic pressures which support them on calm water also make them pound intolerably in rough water, as they impact each successive wave. As summarized by Professor E.V. Lewis[1]

> "In general, planing craft have been poor performers in heavy weather. Although they are often very highly powered, their hull form has prevented their attainment of true supercritical operation. The reason appears to be that the bottom flatness and considerable flare forward prevents the hull from cutting through the waves. Instead, at high speed there is a tendency for the bow to be forced up by the oncoming waves, with heavy bottom slamming following.
>
> "If it were possible to devise a hull that would both plane and cut through the waves, then we could attain high-speed super-critical operation in a small craft. Several requirements should be noted:
>
> (1) Little buoyancy forward
> (2) Relatively small flare at the bow
> (3) No bottom flatness forward
> (4) Extra cockpit protection from boarding seas
> (5) Ample reserve power."

Once one has solved the problem of pounding, so that a planing craft knifes cleanly through a wave, a number of other problems are encountered. Chief among these is the problem of waves which are higher than the boat, so that it is completely submerged as it passes through them. One solution - embraced

*Member, AIAA

**So far as roll is concerned, it has long been good practice to design for "super-critical" operation in normal seas by avoiding excessive metacentric heights.

by Dr. Felix Wankel's hydrofoil boat - is to accept this phenomenon and make everything on deck watertight, streamline, and structurally sound. The other approach - which we favor - is to devise a hull form which will smoothly respond to waves which exceed a given height, and provide a surface at the bow capable of generating a sufficiently high lift force to prevent the bow being submerged. In fact, the hull should act like a low-pass filter and should be subcritical to large waves and supercritical to smaller waves.

The Environment

We are concerned here with vehicles which travel over the ever-changing surface of the sea. Figure 1 is a reminder of what it can look like in lay terms, while Figure 2 and Table 1 present aspects of a more quantitative nature.[12] Nature mercifully provides us with a wave steepness limitation; when the wave height reaches one-seventh of its length, the accelerations required of the water particles become too large for gravity to restrain, and the wave crest disintegrates.[3] But if we wait long enough, or look in the right places, we can encounter waves over one hundred feet in height.[3] Even more dangerous, we can find troughs or "holes" into which quite large ships can plunge, sometimes never to reappear.

It is difficult to design a boat which will operate safely in this environment, and the difficulty increases with speed. So instead of devising a vehicle which is efficient on calm water, and then modifying it, or incorporating features intended to make it seaworthy as well, our approach has been to design a hull for operation in waves, and to let the calm water performance fall where it may.

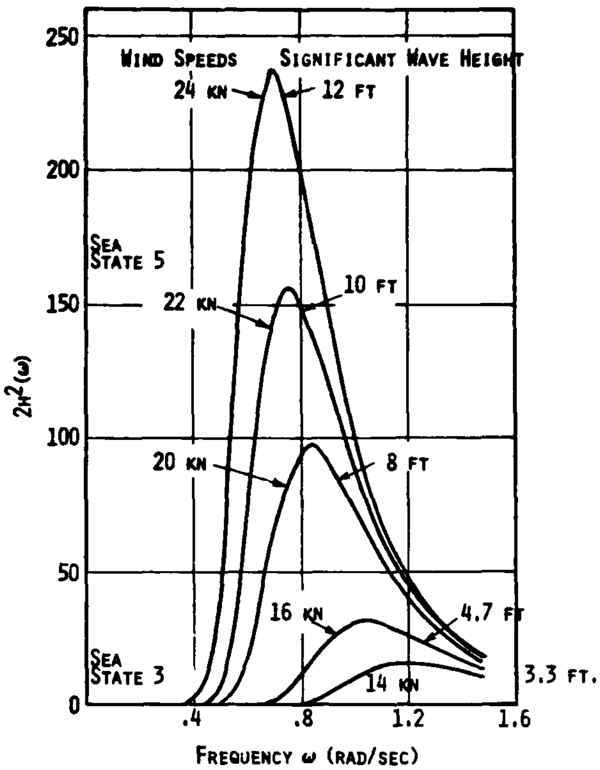

FIGURE 2. PIERSON-MOSKOWITZ[12] FULLY-ARISEN SEA, FIXED-POINT SPECTRA.

Table 1. Wind and Sea Scale for Fully Arisen Sea

(Condensed From Reference 12)

Sea State	Wind in Knots	Wave Height in Feet: Average	Significant	Average 1/10 Highest	T_{max} (secs)	T_{av} (secs)	ℓ_{av} (ft)	Min Fetch (miles)	Min Duration (hours)
1	5	0.18	0.29	0.37	2.0	1.4	6.7	8	0.32
	8.5	0.6	1.0	1.2	3.4	2.4	20.0	9.8	1.7
2	10	0.88	1.4	1.8	4.0	2.9	27	10	2.4
	11	1.4	2.2	2.8	4.8	3.4	40	18	3.8
	13.5	1.8	2.9	3.7	5.4	3.9	52	24	4.8
3	14	2.0	3.3	4.2	5.6	4.0	59	28	5.2
	16	2.9	4.7	5.8	6.5	4.6	72	40	6.6
4	18	3.8	6.1	7.8	7.2	5.1	90	55	8.3
	19	4.3	6.9	8.2	7.7	5.6	99	65	9.2
5	20	5.0	8.0	10	8.1	5.7	111	75	10
	22	6.4	10	13	8.9	6.3	134	100	12
	24	7.9	12	16	9.7	6.8	160	120	14
6	24.5	8.2	13	17	9.9	7.0	164	140	15
	26	9.6	15	20	10.5	7.4	188	180	17
	28	11	18	23	11.3	7.9	212	230	20

T_{max} = Period of Maximum Energy of Spectrum

ℓ_{av} = Average Wave Length

T_{av} = Average Period

All Wave Heights are Trough to Crest

Our Approach to the Problem

We started to study the super-critical hull problem ten years ago because we felt that there was a need for higher speeds in the realistic ocean environment, but that the new vehicle concepts then being advocated might not be the best solution. So often the simplest solution is the best solution, and a hull and a propulsor are the irreductable minimum.

We decided that our first design - a supercritical displacement hull - should be built large enough to carry a crew. One reason, oddly enough, was cost. If the work load in the shop of a small company is rather light for a while, it is sometimes much cheaper to build a "full size" boat than to contract for model tests. Once the boat is in being, pretty fair estimates of its resistance can be obtained in various ways, such as reacting the propeller thrust through an hydraulic cylinder. But, of over-riding importance, in our view, is that the boat can be operated extensively by the designers, in scale seas up to and including severe gales, and a rather complete picture of its virtues and vices obtained. The seat of the pants and the eyeballs of a knowledgeable crew member, especially an ego-involved designer, constitute first class instrumentation which is too often neglected.

Other cogent arguments for manned models have been presented by Dr. F. Marbury, Jr. in connection with the Litton TRISEC program, in a thoughtful paper which is well worth reading.[4] A key argument is that a radically new concept often conceals an unexpected operational vice which one would like to find out about as soon as possible. Manned model testing is the quickest way to do so.

In connection with our most recent design, Table 2 rather crudely indicates the type of seas required for the eighteen-foot prototype, if it is being used as a model of a seventy-five foot craft. Those familiar with Chesapeake Bay, where our plant is located, will recognize that the spectrum required is readily available to us.

In parallel with building and testing manned models, we have placed as much emphasis as we could afford on developing theoretical methods for predicting performance, loads and motions. We calculate the forces from first principles,* rather than empirical curve fits to test tank data, partly because it is the elegant way to go, but overridingly, because we have very little test tank data! We seem to have achieved a measure of success in this theoretical work. Our last completely new design was the Sea Knife, which performed exactly as anticipated from the moment it was launched.

Of course, there is still much theoretical work left to be done, together with a great deal of fundamental model testing. Planing craft have been sadly neglected in hydrodynamics, ever since the demise of the flying boat, and a small group like ours can only contribute so much.

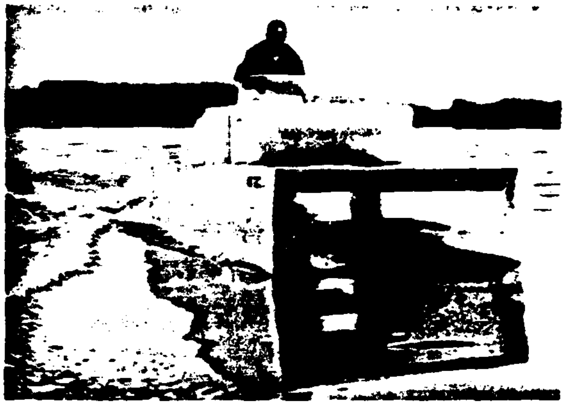

Figure 3. FICAT II, built in 1965, gave a level ride in head seas as high as its floats. The foil across the bows was found necessary when encountering waves higher than the floats. This 17-ft long craft made 20 knots on about 12 thrust horsepower. The fuss seen around the starboard bow was caused by a submerged dent in the bow, caused by a collision with the dock.

Table 2. Sea State Scaled to the 18 Ft. L.O.A. Sea Knife Prototype As a Model of a 75 Ft. L.O.A. Craft

Sea State	Wave Height in Feet			Average Wave Length in Feet
	Average	Significant	Average 1/10 Highest	
1	.04 - .14	.07 - .24	.09 - .29	1.6 - 4.8
2	.21 - .43	.34 - .70	.43 - .89	6.5 - 12.5
3	.48 - .70	.79 - 1.13	1.01 - 1.39	14.2 - 17.3
4	.91 - 1.03	1.46 - 1.66	1.87 - 1.97	21.6 - 23.8
5	1.20 - 1.90	1.92 - 2.88	2.40 - 3.84	26.6 - 38.4
6	1.97 - 2.64	3.12 - 4.32	4.08 - 5.52	39.4 - 50.9

[The largest steep, breaking wave encountered by the 18 ft. boat was about 6 ft. It has also negotiated the wakes of destroyers (about the same height, but quasi-sinusoidal) and extensive high speed operation in gales with average 3-4 ft waves.]

*An example is the derivation of planing surface heave and pitch derivatives in Reference 5.

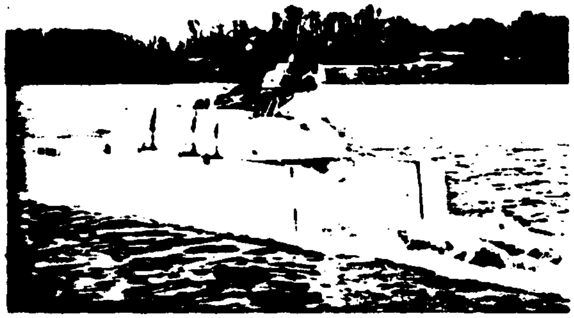

Figure 4. Shown here making 20 knots, FICAT II was airscrew-propelled in order to simplify observation of hull hydrodynamics. The plume of spray is caused by the high energy intersection of the two bow waves under the wing, and represents a reduction in the wave drag cancellation effect at the higher Froude numbers.

The FICAT Displacement Catamaran

Although not a planing hull, the FICAT (Favorable Interference CATamaran) was our first supercritical hull, and operated well into the speed region where dynamic forces become important. FICAT I was launched in 1964; FICAT II, illustrated in Figures 3 and 4, in 1965. We had two objectives in mind; supercritical pitch response, and partial cancellation of the hull-generated wave drag, in the spirit of the Busemann biplane supersonic airfoil, and later as attempted by D. and A. Locke in the sailing catamaran "Tweedle-Dum."[6] We were not then aware of the various papers which said this couldn't be done, and were able to achieve a 50% reduction[7] in wave making drag at a Froude number ($u_o/\sqrt{g\ell}$) of 0.62. Above that speed, the two intersecting bow waves broke upwards in a plume of spray, and the water lost in this way was not available to reflect back to the sterns, resulting in a degradation of the cancellation effect. We only scratched the surface of this problem at the time, and I think it likely that a combined theoretical and experimental program would enable wave-making drag to be almost eliminated at moderate Froude numbers.

Note in Figures 3 and 4 that although the craft is making 20 knots, the water surface is undisturbed along the flat outboard float surfaces, and that, although a bow wave is made by the inboard surfaces, there is no spray at the bow. This is because the entry is so fine that the bow angle is practically zero. The equation for the offsets on this inner surface is

$$\eta = 16(\xi^2 - 2\xi^3 + \xi^4)$$

a waterplane shape which has some rather unusual characteristics. One is that, according to slender ship theory[8,9] a mono-hull so shaped has zero wave drag up to a Froude number of F = 0.27.

As must be obvious from the lines, the pitch and heave response of the FICAT was quite linear. This made resonance quite exciting, and required the bow-mounted foil (Figure 3) both as an amplitude limiting device in resonance, and as a means of lifting the bow to waves larger than the "design" height.

As test speeds reached beyond 20 knots (F = 1.4) FICAT II entered a region of dynamic instability where she would suddenly dig her bow in as far as the foil, and come, as they say, to a screeching halt. I believe we christened this a "plough-in" some years before the word entered the SES lexicon. It was traced to dynamic (suction) pressures on the bottom, which cause the familiar squatting, but which also contribute an unstable pitching moment. When the speed is high enough for the unstable dynamically-induced moment to exceed the stable hydrostatic moment, a "plough-in" occurs. It may be of interest to note that in tracking this down, we used wind tunnel models to determine the pressure distribution over the hulls at different trim angles, simulating the water surface with a "ground-plane."

The 40-knot FICAT aircraft carrier shown in Figures 5 and 6 is typical of our thinking six years ago. But already, in 1967, a new approach to high speeds in waves had attracted our interest, and the FICAT program, which had attracted very little interest in the Navy, was allowed to fade away. Hopefully, some of the technology may be of value in the design of future high speed displacement ships.

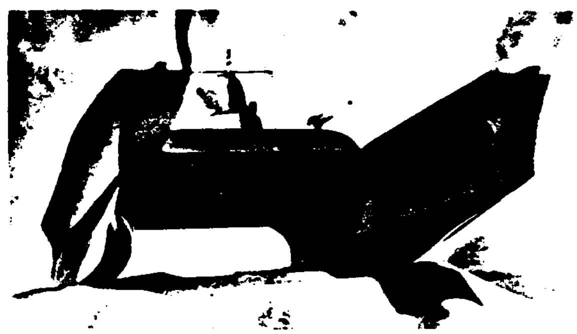

Figure 5. A design for a 40-knot FICAT aircraft carrier.

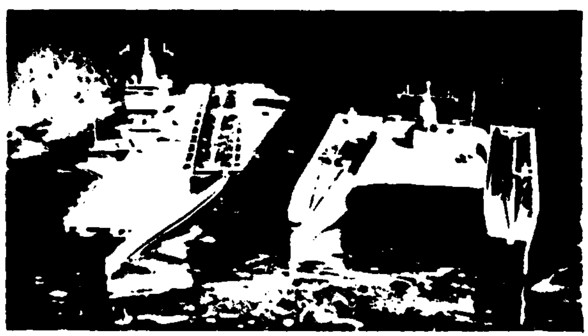

Figure 6. The FICAT carrier to the same scale as the U.S.S. Enterprise.

The GAYLE Boat

In 1967, I conceived the GAYLE Boat design[10] illustrated in Figures 7 through 13. Although the objectives were the same - a smooth ride at high speed in waves - the logic of the various

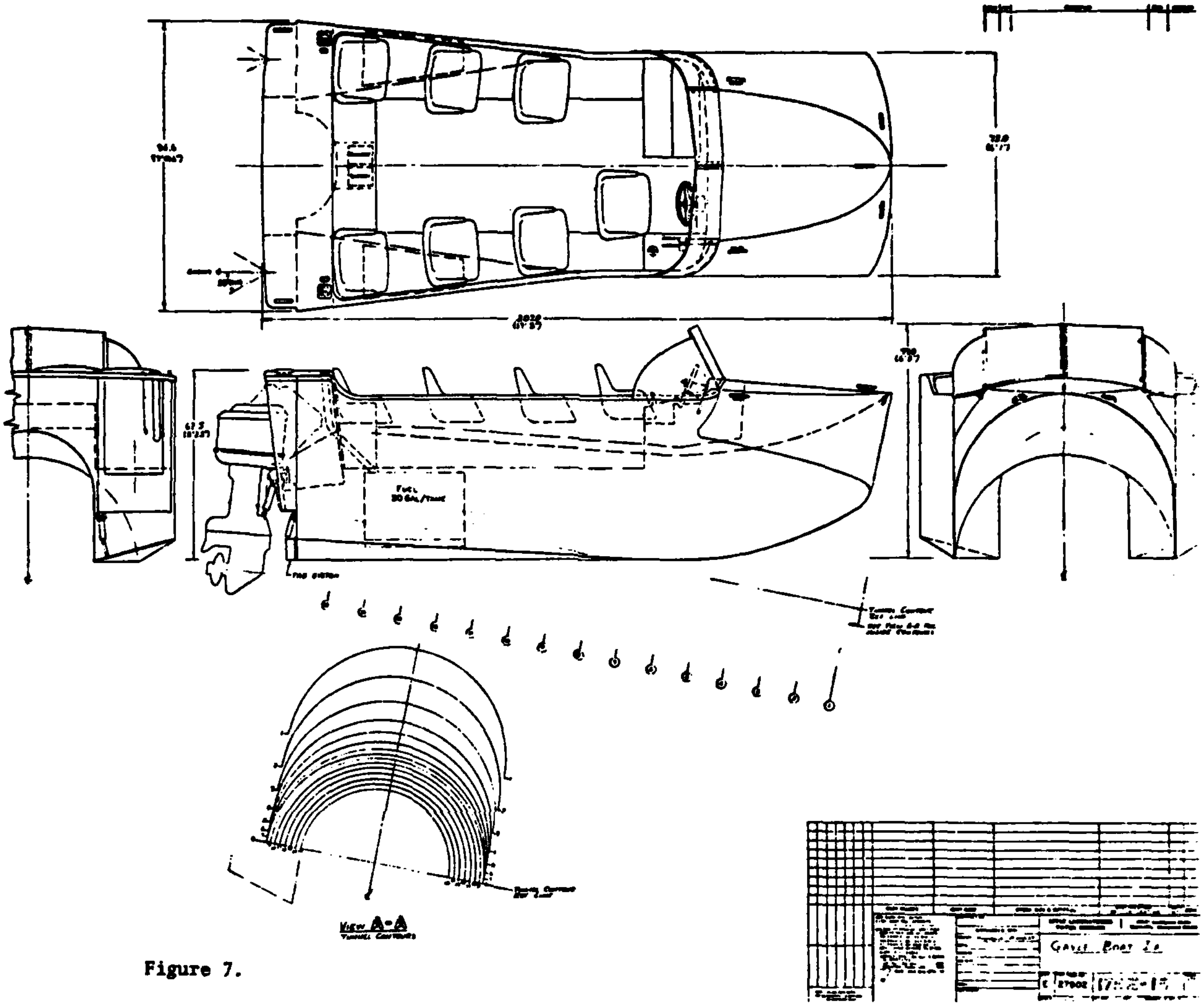

Figure 7.

Figure 8. GAYLE Boat IA on calm water.

Figure 9. GAYLE Boat I making 40 knots in 2-foot waves.

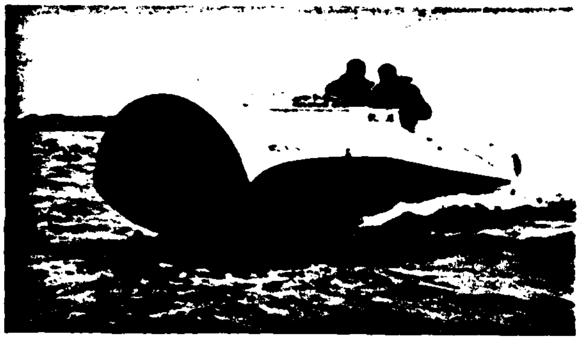

Figure 10. The "slicing" action of the supercritical hull is illustrated here as GAYLE Boat I cuts through a wave at 40 knots, instead of pounding over it, as would a conventional boat.

requirements for safety and seaworthiness, and the fact that wave drag cancellation was not necessary in a planing craft - led to an entirely different set of lines than the FICAT. Altogether, seven GAYLE Boats were built, four of which had a common wing.

In a legal sense, I was the "inventor" of the GAYLE Boat - named after Mrs. Gayle Ann Wayne, our Business Manager - but many other people made vital contributions - had eyes to see where I was blind - and without these contributions, the boat would have been much less successful. Principal among these people, in order of technical contributions, were our Vice President, Edward G.U. Band; Vice Admiral E.P. Aurand; Ken Eldred;* and Alastair Anthony.

Additionally, Peter R. Payne Inc. was acquired by Wyle Laboratories in 1968, and much of the GAYLE Boat development work was carried out with funds provided by Wyle's corporate management. Wyle's diverse operations enabled extensive operating experience to be obtained in the Pacific and the Atlantic, as well as from our own base on Chesapeake Bay. The acceleration data in Figures 41 to 43 was abstracted from results obtained by the Hampton Division in Hampton Roads, for example. This corporate marriage was dissolved in January 1971, and Payne Inc. resumed operations as a separate corporation, having no external ties.

Figure 11. A GAYLE Boat variation designed and built by the Lyman Boat Works of Sandusky, Ohio.

GAYLE Boats I and IA were particularly impressive in rough water, as Figure 41 attests, and in three years of operation, never encountered conditions severe enough to make them slow down. In 1969, GAYLE Boat I was demonstrated to personnel of the U.S. Navy Little Creek Small Boat Engineering Department, making 40 knots in five foot waves. Most of the staff were actually on the boat in these conditions.

Figure 12. The short coupled GAYLE Boat II was unsuccessful, due to violent porpoising.

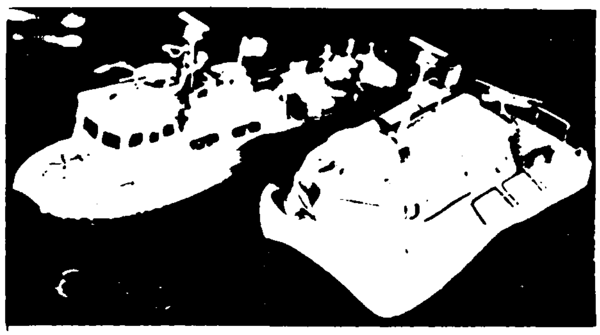

Figure 13. A design study for a GAYLE patrol boat resulted in a craft 35 feet long, costing about the same as the Swift patrol boat shown here in the same scale. The GAYLE Boat was designed to make 50 knots in 5-foot waves. Low speed draft was the same for both vessels.

Although they could cruise at unheard of wave height to boat length ratios (1/3.5), the GAYLE Boats had a number of disadvantages:

- Like all catamarans, they could not bank adequarely in tight turns, and the centripetal acceleration was disconcerting to passengers. In rough water, a tight turn could

*Now Vice President, Bolt Berenek & Newman, Cambridge, Massachusetts.

result in "lateral pounding" as well. Because vertical pounding had been virtually eliminated, lateral accelerations were highly "visible."*

- Although they did not resonate in roll, the boats tended to track the water surface in quartering or beam seas. Although this was better than a conventional small boat hull, it still gave rise to considerable accelerations.

- The hull developed large aerodynamic forces near the bow, when travelling against the wind. Running at 40 knots into a 30 knot head wind resulted in an aerodynamic lift on the bow equal to about one-third of the total displacement. This resulted in trim changes with changes of heading relative to the wind, which had to be countered by adjusting hydraulically operated transom flaps, which was troublesome. Additionally, in storm conditions, one often felt the boat was going to flip over backward when going through hump speed. In fact, this never happened but the extreme trim angle through the hump (into high winds) were felt to be very undesirable.

None of these disadvantages is crippling, particularly in larger craft, which would not want to pull 1-g turns in waves one third their length, and where the aerodynamic lift could be used to advantage, because of longer response times. I'm sure that it has not escaped attention that Figure 7 looks very much like the lines of a fine Captured Air Bubble (CAB) craft, albeit with front and rear seals removed. Also, the "wet deck" is arched, but those familiar with CAB wet deck loading cases might not consider this a disadvantage.

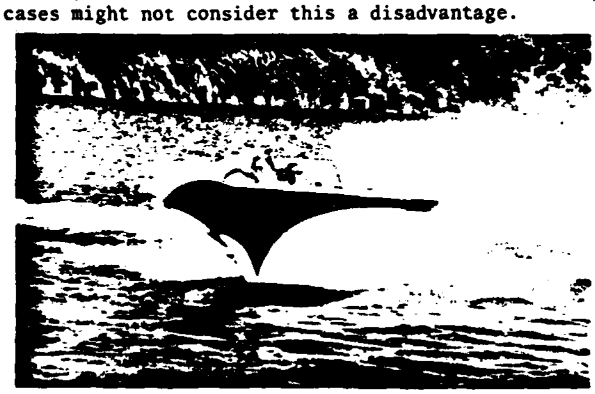

Figure 14. The 18-foot L.O.A. plywood Sea Knife prototype, launched 16 April 1971. The "bow transom" performs the function of the FICAT's bow hydrofoil of Figure 5, in lifting the bow on top of very large waves.

The Sea Knife

Early in 1971, we decided to design a supercritical planing boat suitable for sale in the pleasure boat market, where we anticipated - erroneously as it turned out - less customer resistance. Although the engineering team was the same, financial reasons led us to put this work into a separate corporation, Blade Hulls Inc., which owns all rights to the patent.

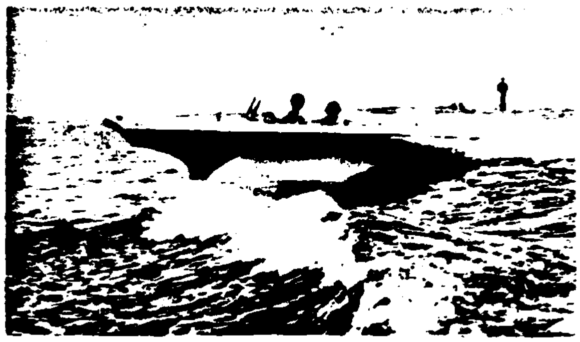

Figure 15. 21 foot, 9 inch L.O.A. "Sea Knife I," launched in the fall of 1971. This craft is of all-aluminum construction.

Work on the new boat - eventually christened Sea Knife - started on 15 February 1971. Our intention was to develop a single-engined, monohull runabout which would have seakeeping characteristics at least as good as the GAYLE Boat, and yet avoid the disadvantages outlined above. Because of the extensive body of theory developed, the design phase went quickly, and work on the prototype commenced 1 March 1971. The prototype was launched on 16 April 1971, and except for a slight tendency to porpoise laterally in a tight turn, performed as intended from the start. There was no need to make CG of trim adjustments, and the boat was untouched until we started to use it for experimental configuration changes in the summer of the following year.

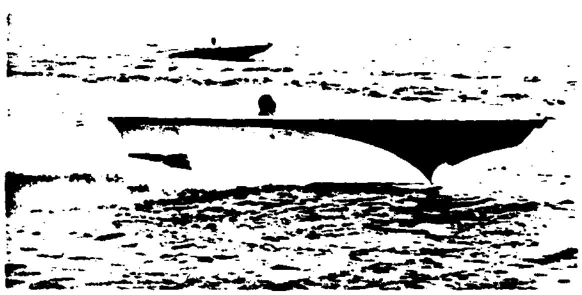

Figure 16. Sea Knife "Scorpion" demonstrating directional stability with no one at the helm. "Scorpion" was built for Mr. Peter Nomikos of London and Athens, and is carried aboard his yacht "Northwind II" in the Mediterranean.

*An extreme case occurred when Commander Farber of SBED, flat out, turned off a five-foot wave and "flew" sideways until we hit the next one. After this incident, the bench seats were taken out, and bucket seats substituted.

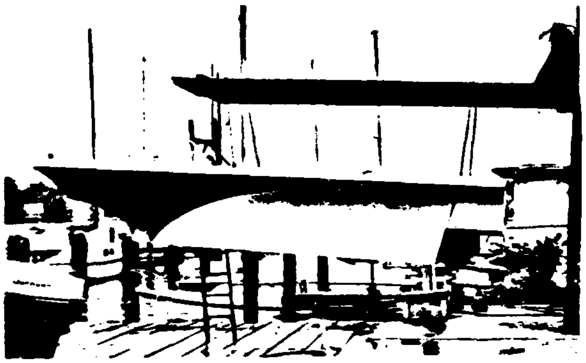

Figure 17. The six-meter Sea Knife, built for Japan Aircraft Company of Yokohama, Japan. Both bustle and bow are truncated, relative to previous boats, to bring the length down to 19 ft, 6 in. These changes - requested because Japanese purchase tax jumps from 10% to 40% at six meters - caused some degradation in calm water stability and maneuvering ability.

Since then, other Sea Knives have been launched, some illustrated in Figures 14 through 19, and our small team has continued to develop the technology and perform design studies for larger Sea Knife hulls. As an example of this work, Figures 20 and 21 show the structure and general arrangement of a 200-passenger, 92-foot L.O.A. ferry.

One of the most interesting developments has been in the successful development and use of the lateral spray sheets which are characteristic of the Sea Knife. "Spray" is really a misnomer, creating an impression of discrete droplets, but it is hard to think of an alternative word which is not ponderous and forced. So, retaining the word, we note that the spray sheets consist of solid water, and provide the chief source of roll stability at speed. Figure 22 provides a rather graphic illustration of how the outer spray sheet stabilizes the boat in a turn, and also gives some indication of the amount of energy it contains. Much of this energy is wasted in the original configuration, since the sheet is allowed to fly off the gunwale horizontally. Additionally, a skin friction penalty is paid in the increased wetted area. These considerations were appreciated in the design stage, but since we were aiming for a highly maneuverable runabout which would travel smoothly in waves of height comparable to the gunwale height, no attempt was made to reduce the losses.

As interest in larger boats for commercial applications developed, the need for higher efficiencies became apparent and a program to develop spray sheet reversers was started. These reversers, illustrated in Figures 23 through 25, were originally intended to recover substantially all of the vertically oriented momentum as dynamic lift. It was then realized that, if the reverser had a bow-down slope to it, not all of the vertical momentum would be recovered, but the force that was reacted would be forwardly inclined, reducing the net pressure drag. We expected to find an optimum bow-down angle for minimum resistance.

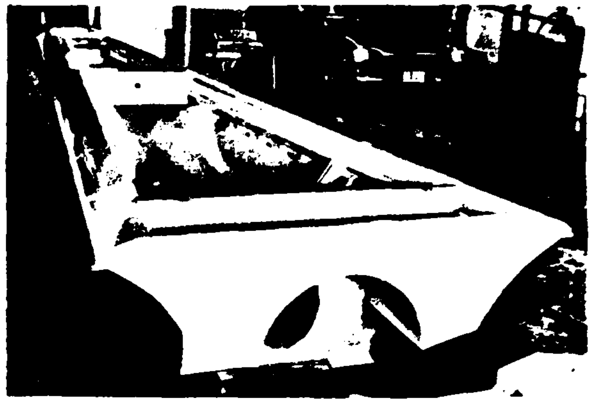

Figure 18. The "six meter" boat leaving the paint shop. This is the entire load-carrying structure for the aluminum Sea Knives; the removable engine firewall and the deck hatches are not load-carrying.

Figure 19. The first fiberglass Sea Knife, built in England by Sandrock Auto Marine, Ltd. of Winchelsea, Sussex. In this model, the bow transom area has been reduced by sweeping down the forward deck line.

An additional advantage of inclining the reverser bow down (when the shape is similar to that shown in Figures 23 and 24) is that it does not experience an additional lift force when passing into the flank of a wave.

Figures 26 and 27 show how one particular set of reversers performed in practice. In the configuration shown, and without changing the propeller, the top speed of the boat increased from 32.0 mph to 41.6 mph with the reversers in place. 41.6 mph corresponds to 74 knots on a 75-ft L.O.A. craft.

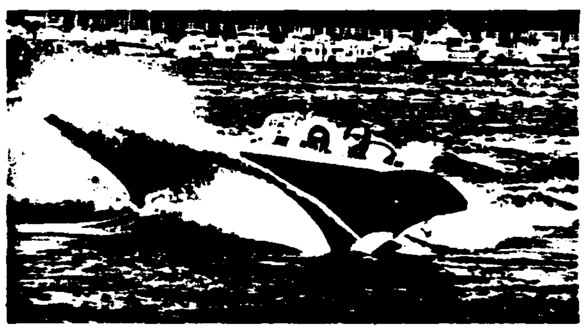

Figure 22. Spray sheet shape, thickened by the side slip developed in a turn, is shown here rather clearly.

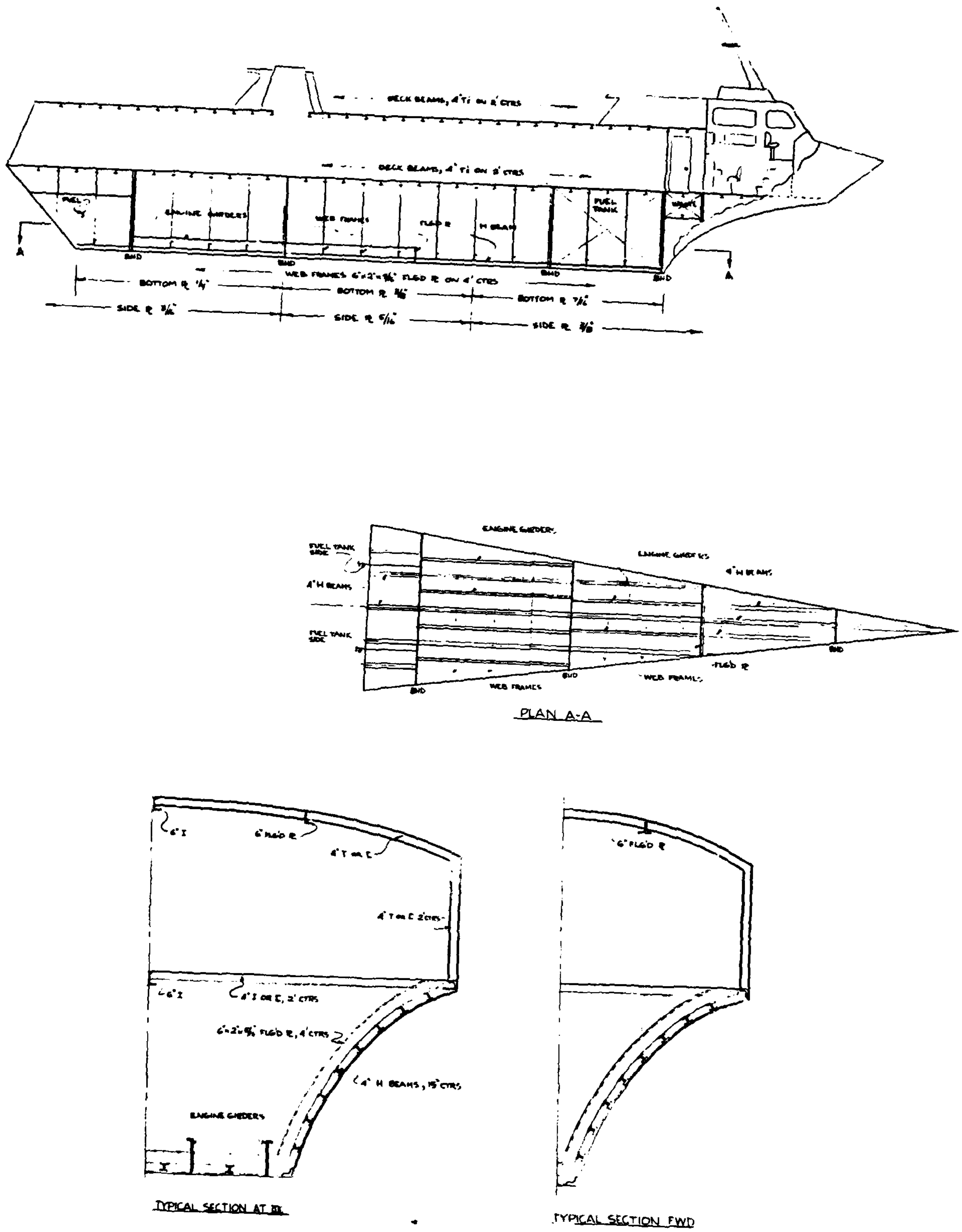

Figure 20. Passenger Ferry, Structural Plan.

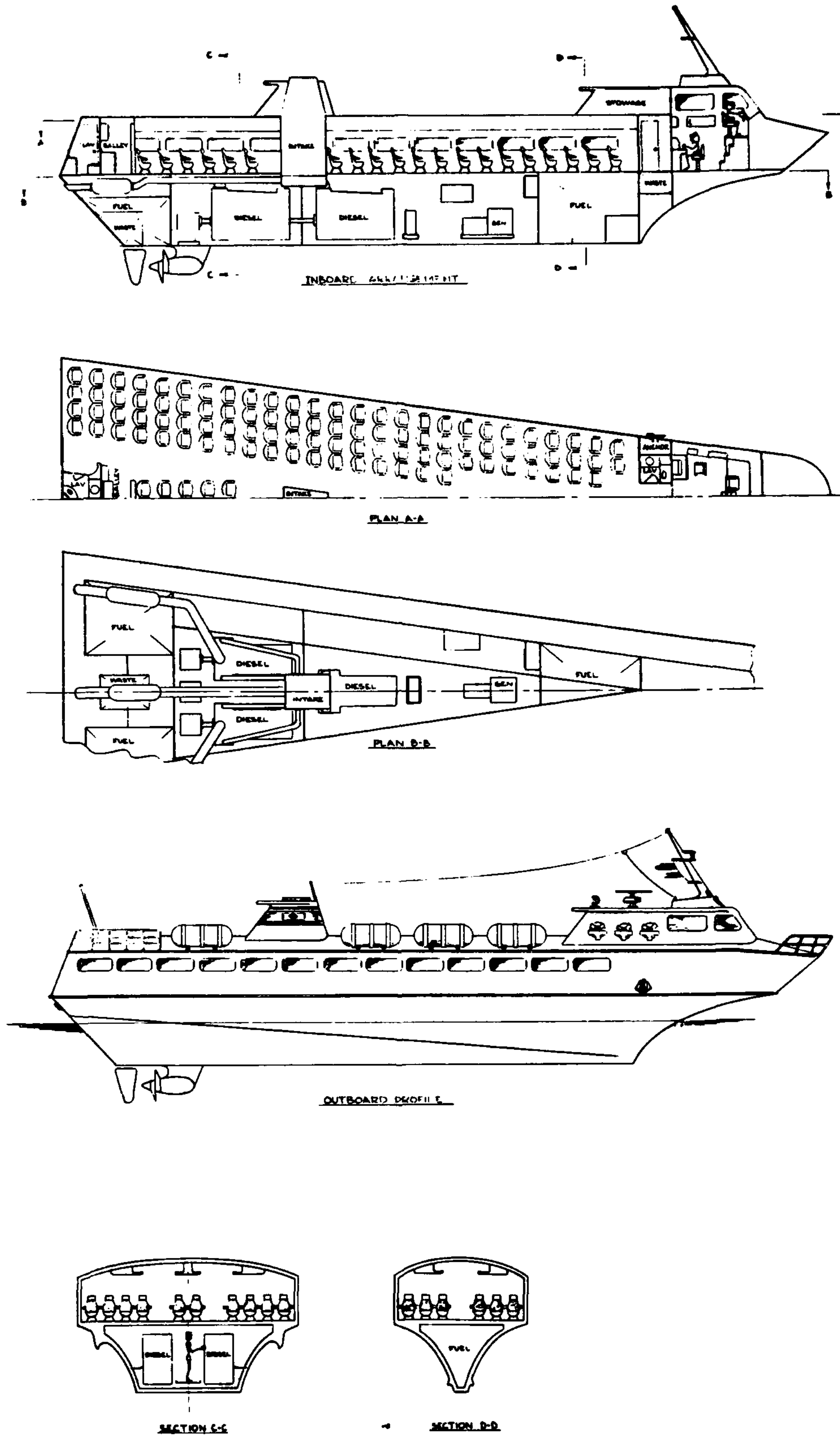

Figure 21. Passenger Ferry, Outboard Profile and Arrangements.

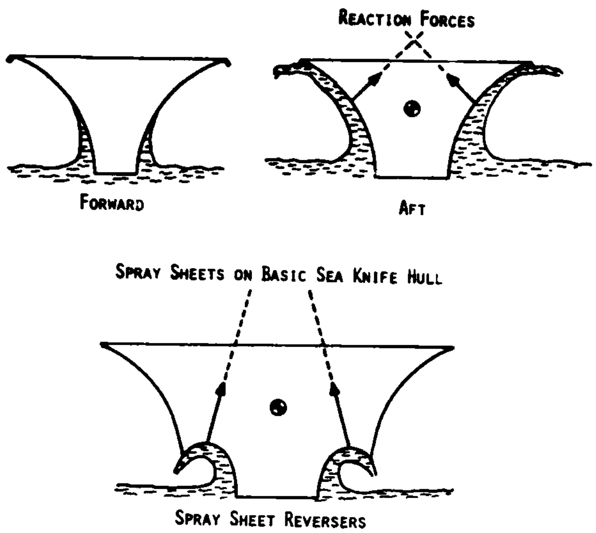

FIGURE 23. THE SEA KNIFE HULL DEVELOPS DYNAMIC LIFT AT ZERO, OR EVEN NEGATIVE TRIM.

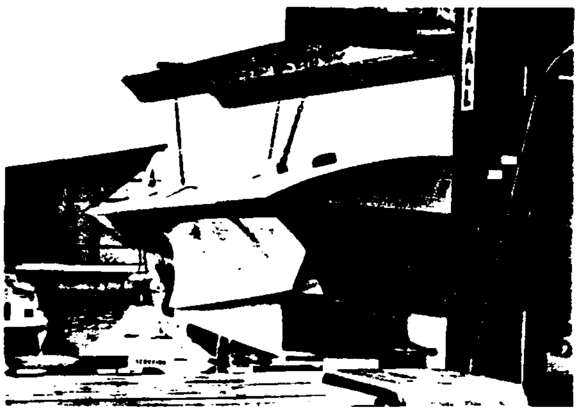

Figure 24. Stern view of spray sheet reversers on Sea Knife "Sylvia."

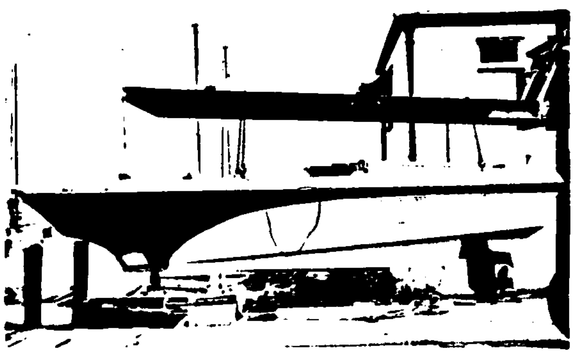

Figure 25. Side view of spray sheet reversers on Sea Knife "Sylvia."

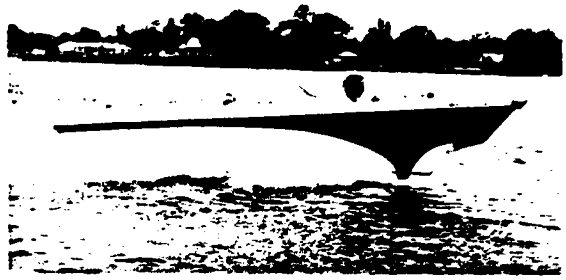

Figure 26. *The spray-reverser-equipped hull at speed.*

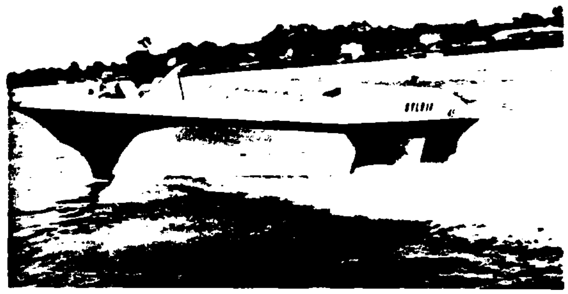

Figure 27. Stern view of the spray sheet reverser action.

The Resistance of a Sea Knife Hull

Calm Water Resistance

We have developed theoretical methods for estimating the resistance of Sea Knife type hull forms at high speeds, when the spray sheet is fully developed. The basic theory, in its present form, is given in Reference 11. The spray sheet geometry is calculated from an "all spray" assumption, giving a discontinuity in the water surface which cannot possibly occur in practice, but is the best approximation available to us at this time.

Because of the relative newness of the technology and the concomitant paucity of experimental data, it is not possible to claim that this theory is completely reliable, but in the limited number of cases where a comparison between theory and practice has proved possible, the theoretical predictions have been confirmed. The following points encourage us to believe that the theory is "good enough" until we can find the time to construct a more rigorous spray sheet model.

- The Sea Knife is, geometrically and hydrodynamically, a very simple shape, allowing theoretical predictions to be made with more confidence than usual.
- The theory is based on basic principles of hydrodynamics; there are no "factors determined from experiment."

• The theory gives sensible answers for simple problems, such as the resistance of cones and the forces on a vertically impacting wedge.

• Theoretical predictions of spray sheet angle to the hull are confirmed by photos of Sea Knives in calm water. Other predicted spray sheet phenomena, such as the thickening of the outer sheet in a turn, are qualitatively confirmed in practice.

• Model test measurements of trim and resistance at the U.S. Naval Academy test tank are in good agreement with the theory.

• A speed increment of nearly ten knots was achieved when spray sheet reversers were fitted to the 18-foot prototype Sea Knife, in accordance with theoretical predictions.

In its present form, the theory is limited to the "design case" illustrated centrally in Figure 28.

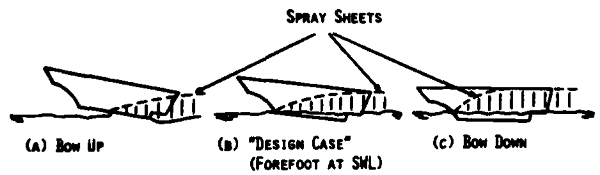

Figure 28. Three Alternative Operating Modes.

In the "design case" trim, all continuity sections of the spray sheet are geometrically similar (but not in absolute size, of course) and determination of the spray sheet parameters is accordingly simplified. There is no particular problem in extending present computer programs to include cases (a) and (c) in Figure 28; merely that other tasks have been assigned higher priorities. We are familiar with the fact that, relative to the design case, the Sea Knives built so far go about 8 knots faster with trim (a), and about 2 knots slower with trim (c). With the forefoot out of the water, trim (a) results in considerable slamming in rough water, and is almost as uncomfortable as a deep-V hull at normal trim.

During model testing, the model was at trim (c) during low speed runs, and only approached the design case at the highest speeds tested. This shows up clearly in the comparison between theoretical and measured trim in Figure 29. Despite this difference, the reduction in pressure drag on the model is just about balanced by the increase in skin friction, and the calculated "design case" resistance is close to the model values, as shown in Figure 30. This agrees with our above-mentioned experience with full scale Sea Knives, which can be trimmed through a wide range of angles by hydraulically tilting the drive strut.

The vertical support components in the model test, according to design point theory, are given in Figure 31 and the corresponding resistance com-

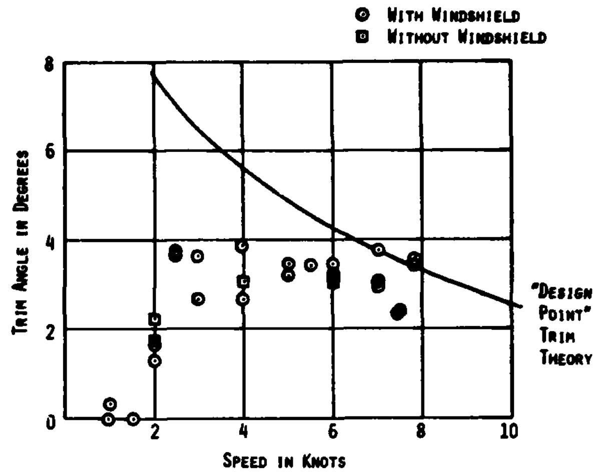

Figure 29. Trim Angle of a 24-Inch L.O.A. Sea Knife Model, as a Function of Speed on Calm Water. (Naval Academy Tow Tank, December 1972-January 1973). (CG at 34.4% Forward of Transom Heel.)

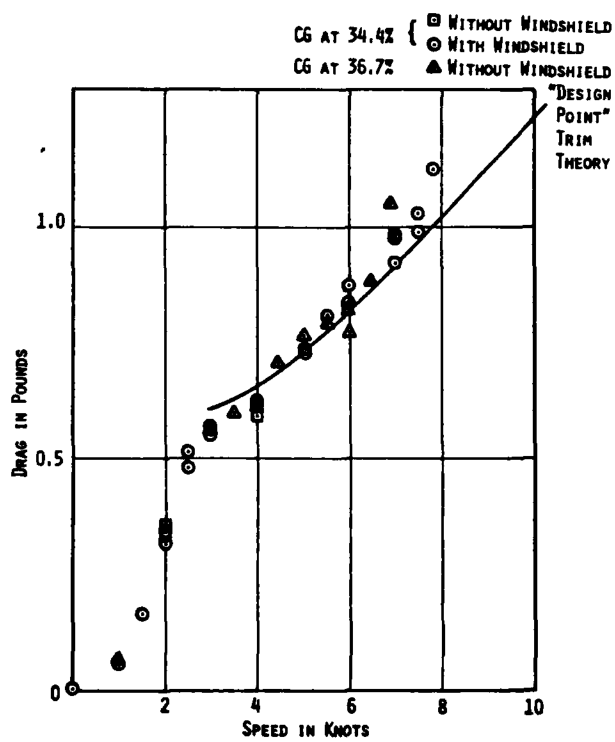

Figure 30. Calm Water Resistance of a 24-Inch L.O.A. Sea Knife Model. (Naval Academy Tow Tank, December 1972-January 1973).

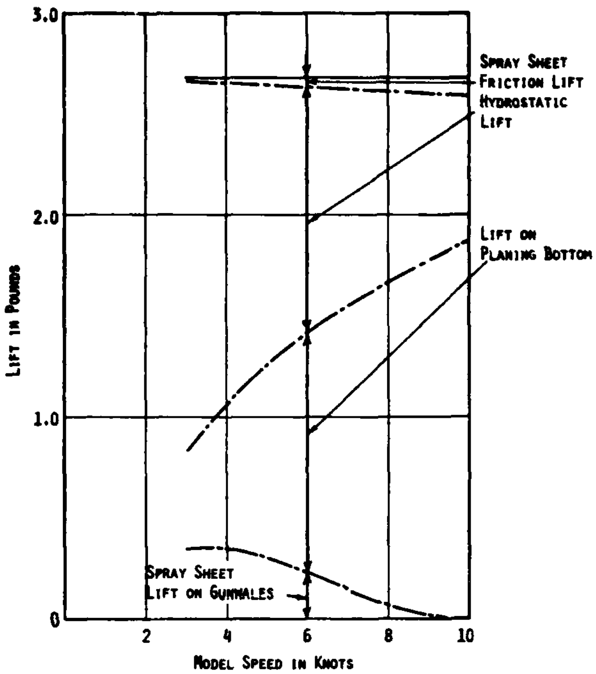

Figure 31. Lift Components for the Sea Knife Model Tests, if the Forefoot Remained at the SWL ("Design Case").

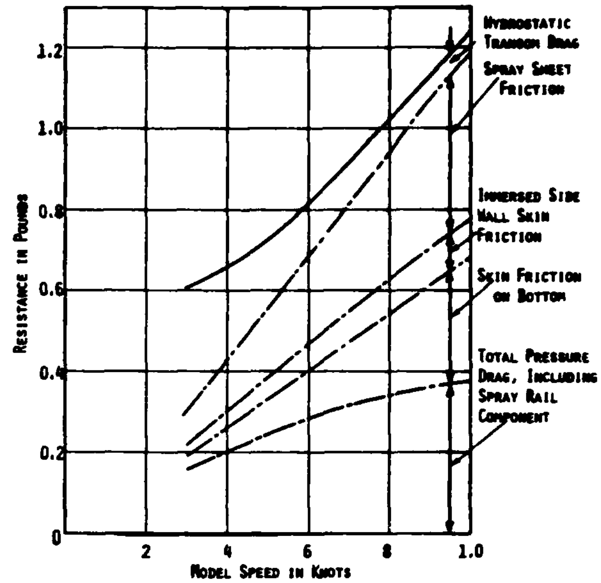

Figure 32. Resistance Components for the Sea Knife Model Tests, if the Forefoot Remained at the SWL ("Design Case").

ponents in Figure 32.* The lift/drag ratios (L/D) corresponding to these values is poor, principally because:

> the model is much too lightly loaded**
>
> the spray sheet wets too large a portion of the model's sides.

To obtain curves (A) in Figure 33, we have applied the test tank data to a 70-ft L.O.A. boat, identical in configuration to that used in the test tank and scaled up in displacement as the cube of the linear scale. It can be seen that maximum L/D is achieved at the lowest speeds, and that the high speed power requirement is excessive.

We then reduced the size of the basic wedge and gunwale height (retaining geometric similarity with the test tank model) and maintained 70-ft L.O.A. by adding a "bustle" to the transom of the basic wedge. This bustle is intended to be clear of the water when the boat is at speed, although its sides are wetted by the spray sheet. The result is shown by curves (B).

To obtain curves (C), the configuration was unchanged, but the gunwale was "rolled over" to discharge the spray sheet almost vertically downwards, at a mean angle of 80° to the horizontal. Due to the increased spray sheet support, this results in a further increase in efficiency.

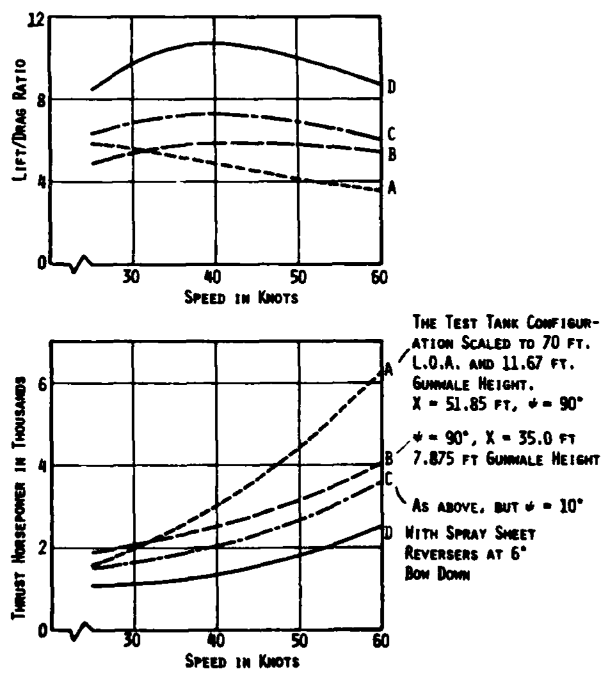

Figure 33. A Comparison of Four 70-Ft. L.O.A. Hull Configurations for Δ = 120,000 lbs., σ = 0.135. Included Wedge Angle = 15.38°.

*The boundary layer was assumed to be fully turbulent on the model. Calm water tests with and without turbulator rakes failed to show any change in resistance.

**The Sea Knife hull form is most efficient when heavily loaded. In the Naval Academy model tests, we selected a compromise displacement which was just within the capability of a Series 62 hull used for comparison.

Finally, to obtain curves (D), a separate spray sheet reverser was placed on each side of the hull, inclined 6° bow down. This resulted in a maximum L/D of 10.6 at 40 knots.

The lift and resistance components of the curve (D) configuration are given in Figure 34. The "hump" indicated at the lowest speeds will not be as pronounced in practice, because below about 35 knots, the bustle would be in contact with the water (an effect not included in the high speed theory) and the forefoot of the bow would be below the water surface, reducing the trim.

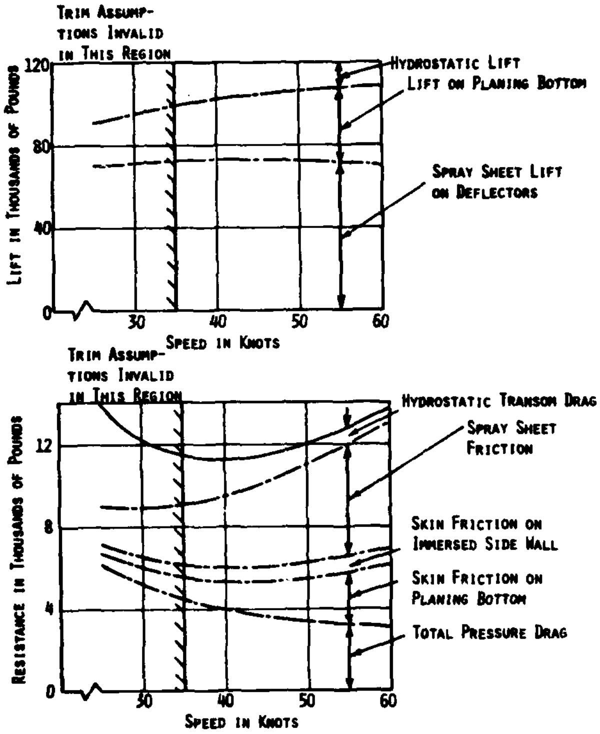

Figure 34. Components of Vertical Force and Resistance, for a 70-ft. L.O.A. Sea Knife with Spray Reversers at 6°; x = 35.0 ft., Δ = 120,000 lbs.

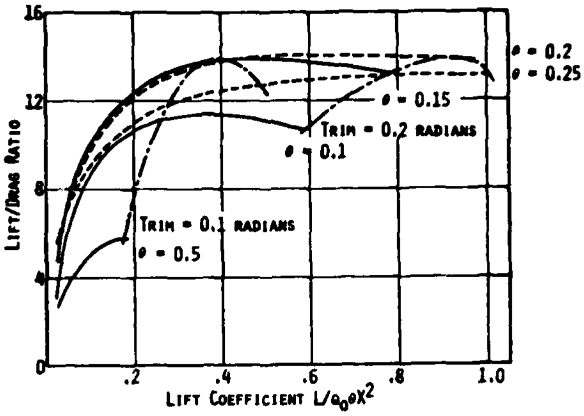

Figure 35. Variation of Lift/Drag Ratio with Wedge Angle θ when the Spray Reversers are at the Optimum Angle for Minimum Pressure Drag on the Sides. $z_0/x = 3.0/51.97$; $x_1/x = 67.0/51.97$.

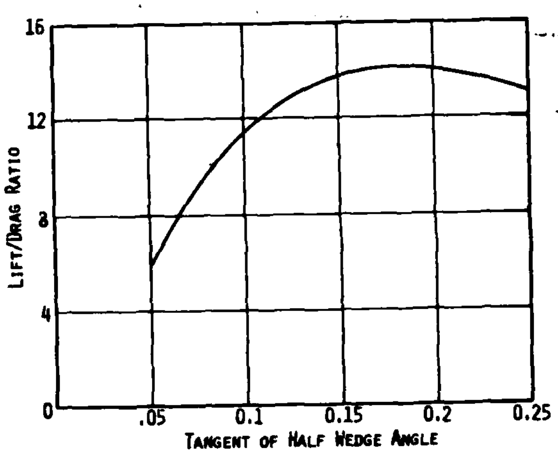

Figure 36. Variation of Maximum Lift/Drag Ratio with Wedge Angle θ for Optimum Spray Reverser Angle.

For comparative purposes, Figures 35 and 36 show the optimum performance which may be obtained from a straight-sided wedge with fully optimized, multi-element spray reversers. Further improvements can undoubtedly be obtained by varying the geometry of the wedge to incorporate camber, and by rounding the chines to reduce wetted area.

Resistance in Waves

When trimmed correctly, the GAYLE Boat catamarans ran faster into moderate head seas than on calm water. The 18-foot and 21.7-foot L.O.A. Sea Knives have partially retained this characteristic, in the sense that they are not slowed by head seas up to four feet in height (corresponding to sea state 7 for a 75-foot craft, or a moderate gale), but many authorities have had difficulty with this admittedly surprising assertion. It was therefore decided to measure the resistance of a basic Sea Knife hull in waves, up to a maximum wave height attainable in the U.S. Naval Academy tank. The totality of the resistance and trim data obtained is given in Figures 37 and 38, in comparison with the theoretical high-speed, "design point" trim predictions.

The wave combinations selected, after some experimentation, were those likely to give most trouble to a supercritical hull at high speed; namely waves with a length of about 3L, where L is the boat length. Wave lengths of 2L and L were also used, in order to cover the region so troublesome to more conventional craft.

For the model tank testing, as shown by Table 3, 2.0 in. and 2.25 in. height waves of 48 in. and 72 in. length were a fair simulation of Sea State 5 for a 75-foot craft. The model ran well under these conditions, and the waves could clearly have been substantially higher without distress

Table 3. Sea State Scaled to the 24-Inch L.O.A. Sea Knife Model as a Model of a 75-Foot L.O.A. Craft

Sea State	Wave Height in Inches			Average Wave Length in Inches
	Average	Significant	Average 1/10 Highest	
1	.05 - .17	.09 - .32	.12 - .39	2.1 - 6.4
2	.28 - .57	.45 - .93	.57 - 1.19	8.7 - 16.7
3	.64 - .93	1.05 - 1.51	1.35 - 1.85	18.9 - 23.1
4	1.21 - 1.37	1.95 - 2.21	2.49 - 2.63	28.8 - 31.7
5	1.60 - 2.53	2.56 - 3.84	3.20 - 5.12	35.5 - 51.2
6	2.63 - 3.52	4.16 - 5.76	5.44 - 7.36	52.5 - 67.9

(The largest wave this model was tested in was 2.25 in., due to test tank limitations)

NOTE: All wave heights are trough to crest.

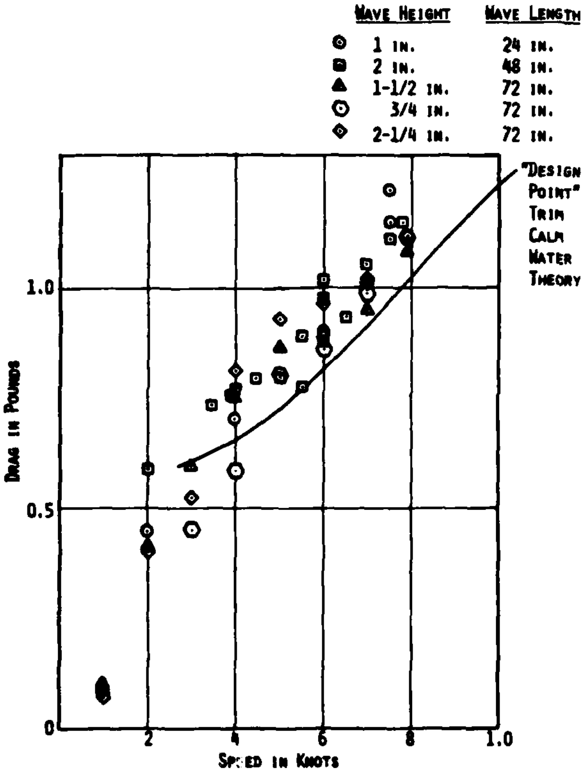

FIGURE 37. ROUGH WATER RESISTANCE OF A 24-INCH L.O.A. SEA KNIFE MODEL. CG AT 36.7% FORWARD OF TRANSOM HEEL. (NAVAL ACADEMY TOW TANK, DECEMBER 1972-JANUARY 1973).

model.* Unfortunately, 2.25 in. was the largest wave which could be made.

To assess the effect of waves on resistance in waves, a least mean squares best fit to the calm water resistance was obtained, as shown in Figure 39. The same kind of fits were then obtained for the resistance in waves, and the resulting means compared in Figure 40. The highest test speed of 7.9 knots corresponds to 23.7 knots on the wooden prototype, and 26.1 knots for the 21.7-ft metal boats; about two-thirds their normal operating speeds.

In Figure 40, we see that, at the highest model speed, where the model can be characterized as "fully planing," the sea state 4 resistance is lower than for calm water, although the difference is comparable with the accuracy of the data. The trends clearly indicate a greater difference at higher speeds, however.

An explanation is supplied by the heave records, where it is found that the mean heave is three times the calm water value; the model is cutting more through the tops of the waves because the dynamic lift in waves is greater, due to transient terms in the equation.

$$\text{Force} = \frac{d}{dt}(mv) = v\frac{dm}{dt} + m\frac{dv}{dt}$$

In calm water, $dm/dt = 0$, so that dynamic lift is obtained by accelerating a mass of water m by the amount dv/dt. But when entering a wave, $dm/dt > 0$,

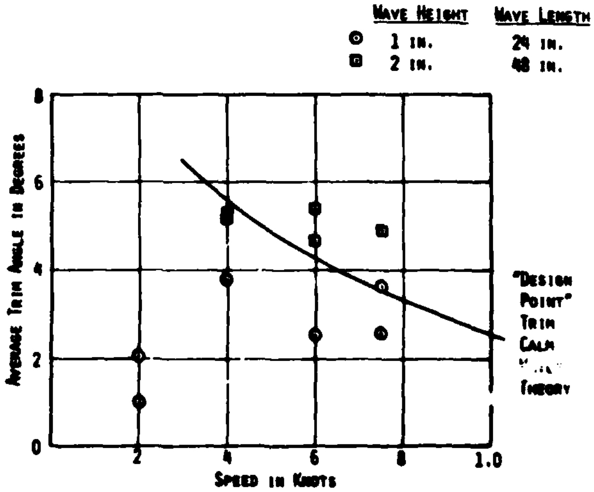

FIGURE 38. AVERAGE TRIM ANGLE OF A 24-INCH L.O.A. SEA KNIFE MODEL AS A FUNCTION OF SPEED, IN ROUGH WATER. (NAVAL ACADEMY TOW TANK, DECEMBER 1972-JANUARY 1973).

*Since this was a supercritical hull form, we always commenced testing in a new wave condition at the highest available tow speed, and worked down to resonance; a procedure which raised some eyebrows.

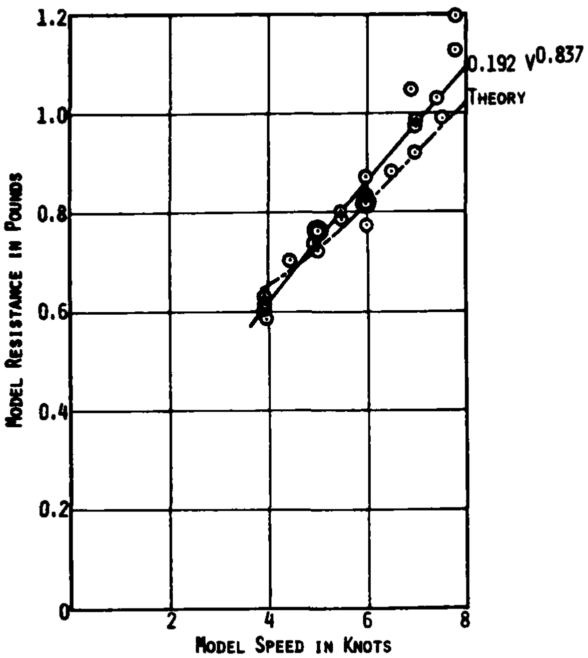

FIGURE 39. LEAST SQUARES BEST FIT TO THE 24-INCH MODEL SEA KNIFE RESISTANCE ON CALM WATER. (NAVAL ACADEMY TOW TANK, DECEMBER 1972-JANUARY 1973).

NOTE: DATA FOR ALL CG POSITIONS IS INCLUDED.

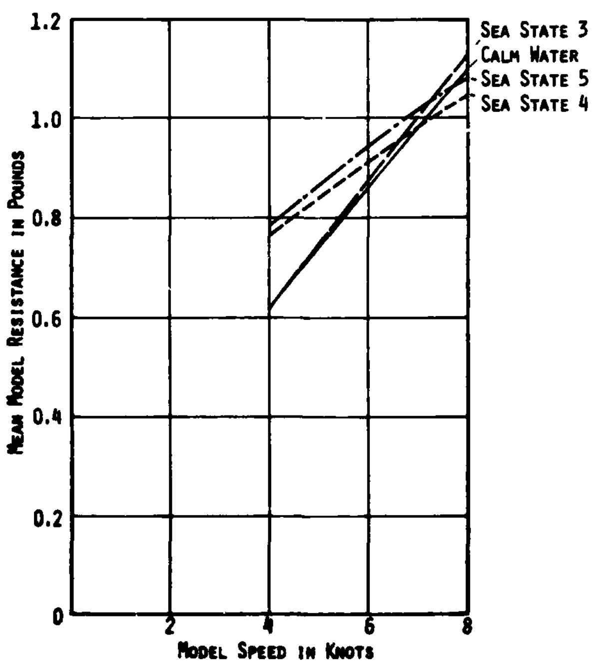

FIGURE 40. VARIATION OF MEAN MODEL RESISTANCE WITH SPEED AND SCALE SEA STATE.

so that the dynamic lift is increased. This transient force can only act in an upward direction as the water will break away from the hull before any significant downward force can develop.

The same effect has been experienced with early seaplane designs and with the large deep-V boats currently used in ocean racing, when the wave length is short enough. Recent increases in the length of ocean racers are partly due to the designer's desire to optimize this effect.

Seakeeping

A principal reason for the ride qualities of the Sea Knife is the fact that its planing lift is derived in part from the heavily loaded planing bottom which is always submerged, and in part from the spray reversers which depend for their lift only on the forward motion of the craft. Passage through waves has little effect on the lift provided from either source, and does not cause such rapid variations of the wetted area as occur on V-bottom boats.

A quantitative illustration of the effectiveness of the concept is provided in Figures 41 through 43 obtained when the earlier GAYLE Boat IA was compared in Hampton Roads with a conventional runabout of similar size. To ensure that an exact comparison could be obtained, the two boats were run side-by-side at equal speeds through identical sea conditions. An accelerometer in the bow of each boat was connected to a single recorder located in the GAYLE Boat. Some of the results of these tests are shown in the figures. While the maximum peak acceleration measured on the GAYLE Boat was about .35g (Figure 42), values of 3g were recorded very repeatedly on the runabout. The speeds at which the tests were run (about 25 knots) were limited by the crew of the runabout refusing to go any faster. The 25-knot speed scales to approximately 50 knots for a 75-ft boat, and the two-foot waves scale to eight feet. No scaling need be applied to the accelerations, which indicates that a 75-ft boat should not exceed accelerations of .35g when running in an eight foot sea.

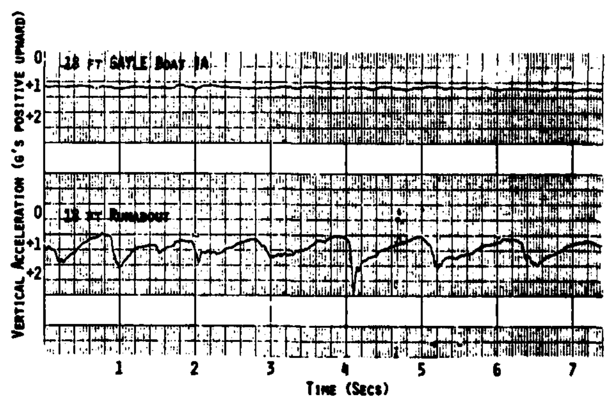

FIGURE 41. COMPARATIVE SEAKEEPING TEST RESULTS (25 KNOTS - 2 FT HEAD SEAS). (BOATS WERE CONNECTED BY 40' HIGH WIRE. RUNNING AT SAME SPEED, IN SAME DIRECTION THROUGH SAME WAVES.)

The Sea Knife, if anything, has a superior rough water performance to the earlier GAYLE Boat. The catamaran configuration of the latter can give rise

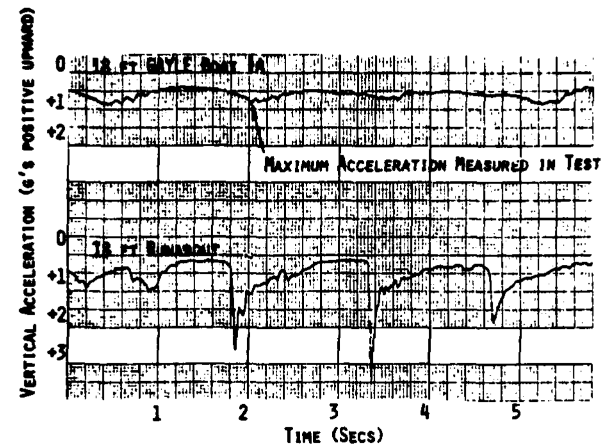

Figure 42. Comparative Seakeeping Test Results (25 knots - 2-3 ft. Beam Seas).

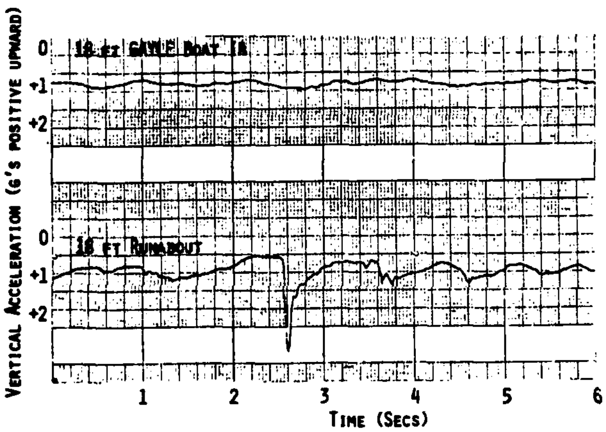

Figure 43. Comparative Seakeeping Test Results (25 knots - 2 ft Oblique Seas).

to a lurching motion when running in quartering seas or when turning at speed - both of which characteristics are absent from the Sea Knife.

Analysis of Seakeeping Model Tests

The two-foot model of the Sea Knife was tested in the U.S. Naval Academy towing tank in a range of wave conditions. Measurements were taken of speed, resistance, heave, trim and vertical accelerations at a location four inches forward of the CG.

Although the runs were of very short duration, due to the limitations of the tank, a reasonable number of wave encounters were recorded. Results of a typical run at 6 knots (model speed) in waves 1-1/2" high and 6 feet long are shown in Figure 44. The acceleration trace is remarkably free from impact spikes. Scaled up to a 90T Sea Knife ship, these runs represent speeds of 28 and 33 knots in regular 4-ft waves. The apparent reduction in wave height during the run is due to ventilation of the carriage-mounted wave probes, which becomes more marked as speed increases.

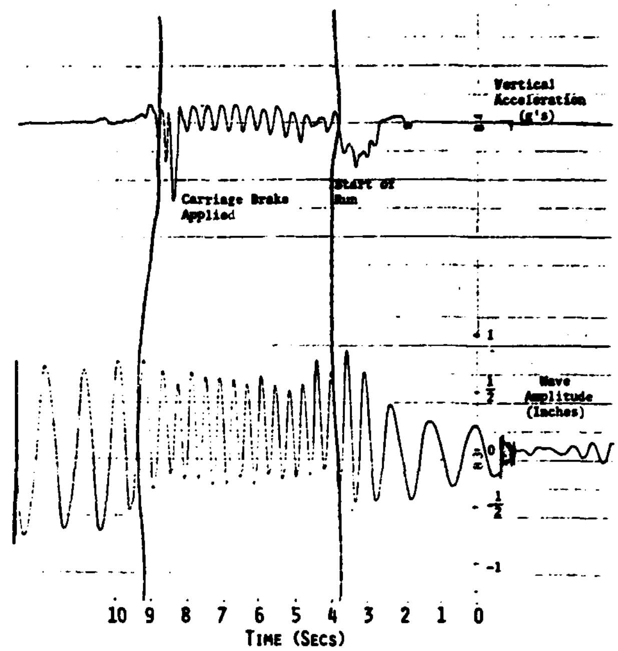

Figure 44. Typical Acceleration Response of Sea Knife Model in Waves at 6 Knots.

In order to assess these results, a series of vertical acceleration transfer functions (or Response Amplitude Operators) were developed by scaling the measured acceleration magnitudes and encounter frequencies to represent a 90T Sea Knife ship. These transfer functions are speed dependent and are plotted in Figure 45, together with a group of similar curves for other types of craft (Reference 13). The only craft that gives superior ride characteristics is the sophisticated fully-submerged hydrofoil, which, after all, employs the same principle as the Sea Knife in minimizing vertical response to waves.

By conducting a conventional linear-superposition analysis, it is possible to compound the RAO curves with the typical wave spectra shown in Figure 2, to obtain response spectra and to integrate these response spectra to predict the r.m.s. CG accelerations as a function of speed and sea state (Figures 46 and 47). Alternatively, these results can be plotted on an acceleration tolerance chart to demonstrate that the behavior of the Sea Knife in waves will disturb the crew less than most other forms of ocean-going craft (Figure 48).

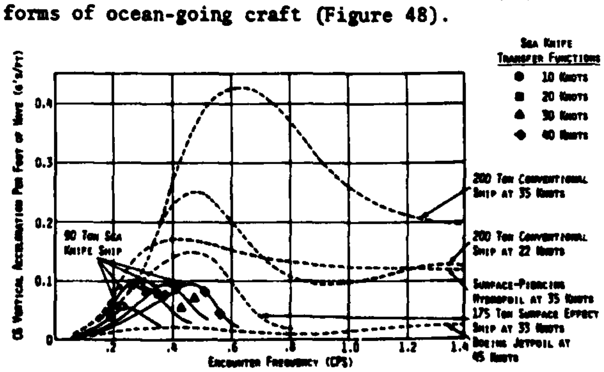

Figure 45. Vertical Acceleration Transfer Functions for Various Ocean-Going Craft.

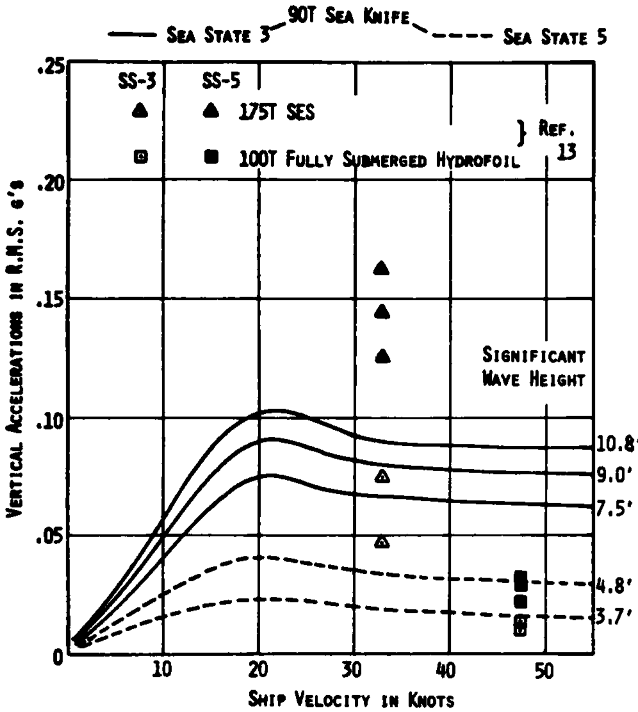

Figure 46. Variation of R.M.S. Vertical Acceleration as a Function of Wave Height and Speed.

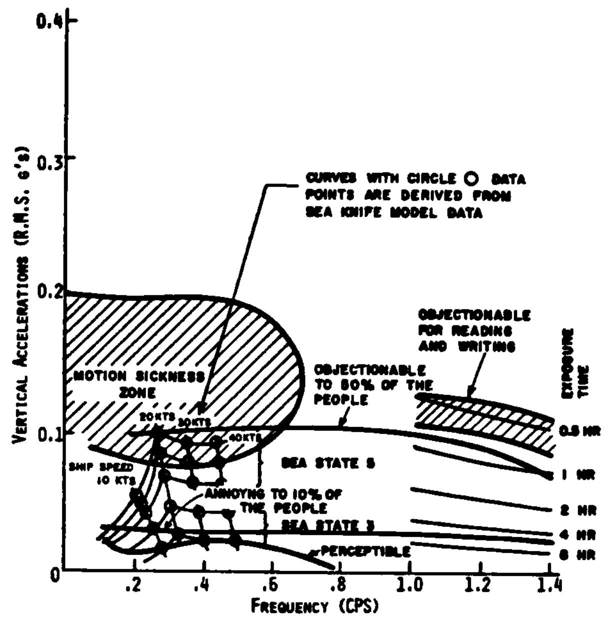

Figure 48. Analysis of Habitability of a 75 ft. L.O.A. Sea Knife in Sea States 3 and 5. (Data from Reference 13)

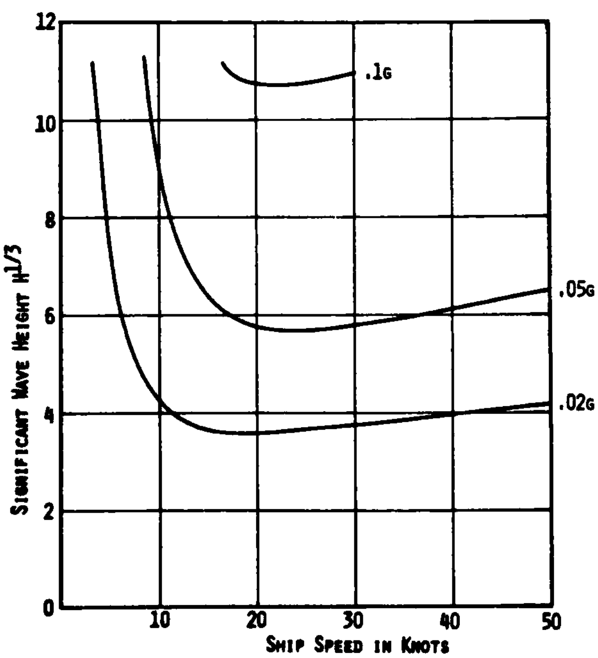

Figure 47. Envelopes of R.M.S. CG Acceleration for a 75 ft L.O.A. Sea Knife.

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Acknowledgements

The model data was obtained in the Naval Academy test tank while it was contractor-operated, and we also performed the data reduction. But, although only Payne Inc. is responsible for the data, we owe thanks to Professor Paul Van Mater and his staff for their invaluable help and assistance. and an apology for breaking the tow arm when the comparative Series 62 hull plunged to destruction during testing in waves.

The work described in the "Seakeeping" section of this paper was contributed by E.G.U. Band, our Vice President. In addition, of course, he has continually made major contributions to the overall program during the last six years.

In testing a new boat to the limit of its maneuvering or seakeeping capabilities, there are times when it is hard to control an instinctive reach for the throttle. My wife Sylvia has been responsible for exploring most of these out-of-operational envelope boundaries, usually because she did it so well, but sometimes, because no one else had the courage. In the Sea Knife program, she proved that it is impossible to turn the boat over; a conclusion later verified (in the same experimental way) by Admiral Zumwalt.

I should also like to pay tribute to my other associates and co-workers, past and present, for their help in this work, often well above and beyond the call of duty. It would be too lengthy to name them all here, and invidious to single out individuals. They have often worked long hours without compensation, for the love of it. Particularly at sea, they have often been wet and cold - new boats always seem to be ready in January - and sometimes frightened as well. Our adventures together would form the basis of a good book, and I hope someone will write it, one day.